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LASER SAFETY THRESHOLDS FOR CETACEANS AND PINNIPEDS

By

Heather M. Zorn, James H. Churnside, and Charles W. Oliver

ADMINISTRATIVE REPORT LJ-98-10C

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LASER SAFETY THRESHOLDS FOR CETACEANS AND PINNIPEDS

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in accordance with

FOP Serial Number 002
issued November 1997

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Explanatory Note

This report is one in a series on the potential for technology applications to enhance efficiency in commercial fisheries, reduce the catch of non-targeted species, and provide new tools for fishery assessments in support of the NMFS strategic goals to build sustainable fisheries and recover protected species. We hope the distribution of this report will facilitate further discussion and research into the application's potential usefulness, but should not be construed as an endorsement of the application by NMFS.

Pursuant to changes in the Marine Mammal Protection Act in 1988, the NMFS' SWFSC began another series of ETP-related studies in 1990, focused on developing and evaluating methods of capturing yellowfin tuna which do not involve dolphins. This series of studies has been conducted within the SWFSC's Dolphin-Safe Research Program. Studies on the potential use of airborne lidar (LIght Detection And Ranging) systems began in 1991, and studies on low-frequency acoustic systems to detect fish schools at ranges much greater than currently possible were initiated during 1995. In addition to their use as an alternative to fishing on dolphins, these systems have potential to increase the efficiency of the fishing operations by locating fish schools not detectable by customary visual means, and as a fishery-independent tool to conduct population assessments on pelagic fish. They also have potential to adversely impact marine animals.

The Dolphin-Safe Research Program is investigating, through a series of contracts and grants, five airborne lidars: 1) the NMFS-developed "Osprey" lidar (Oliver et al. 1994), 2) the Kaman Aerospace Corporation's FISHEYE imaging lidar (Oliver and Edwards 1996), 3) the NOAA Environmental Technology Laboratory's Experimental Oceanographic Fisheries Lidar (Churnside et al. 1998), 4) the Arete Associates 3D Streak-Tube Imaging Lidar, and 5) the Detection Limited's lidar . **An initial study on the potential effects of airborne lidars on marine mammals will be completed during 1998 (Zorn et al. 1998).**

The Dolphin-Safe Research Program has completed, through a series of contracts and grants, acoustic system studies on 1) the acoustic target strength of large yellowfin tuna schools (Nero 1996), 2) acoustic detection parameters and potential in the eastern tropical Pacific Ocean (Rees 1996), 3) the design of two towed acoustic systems (Rees 1998, Denny et al. 1998), 4) measurements of swimbladder volumes from large yellowfin tuna (Schaefer and Oliver 1998) and, 5) the potential effects of low-frequency sound on marine mammals (Ketten 1998).

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Dolphin-Safe Research Program Detection Technology Reports

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Schaefer, K. M. and C. W. Oliver. 1998. Shape, volume, and resonance frequency of the swimbladder of yellowfin tuna (*Thunnus albacares*). Southwest Fisheries Science Center Admin. Rpt. LJ-98-09C 27p.

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ABSTRACT

An increase in the use of oceanographic lidar has raised concern over laser safety for marine mammals. We were able to address some of these concerns by combining information about current laser safety standards, retinal damage mechanisms for humans, and research on eye anatomy for humans, cetaceans, and pinnipeds. To calculate the energy density at the retina, the visual acuity, focal length, and pupil diameter must be known. Visual acuities were obtained from either behavioral studies or ganglion cell studies for six species of cetaceans and five species of pinnipeds. A sensitivity ratio was calculated for each species using the ratio of the energy density at the retina of the marine mammal to the energy density at the retina of humans. The sensitivity ratio was used to suggest exposure limits for the various species. Because the human eye is more sensitive than both the cetacean and pinniped eye, we conclude that laser energies that are eye safe for humans will also be safe for marine mammals, and higher laser energy densities may be appropriate if illumination of humans is avoided.

Key words: Laser safety, cetaceans, pinnipeds, marine mammals, oceanographic lidar, visual acuity.

INTRODUCTION

The use of airborne LIDAR (light detection and ranging) has recently become common in many different oceanographic experiments. Lidar systems are currently being used for hydrographic surveys (Abbot *et al.* 1996, Lillycrop *et al.* 1996, Steinvall and Koppari 1996), fish detection (Churnside and Hunter 1996, Churnside et al. 1997), and fluorescence measurements (Hoge *et al.* 1986, Smith *et al.* 1987). In addition, the military has developed a number of applications for lidar systems. With the laser beam sweeping across the ocean surface, a question naturally arises: What safety measures must be taken to ensure that there are no adverse effects on either humans or marine life?

The planes, which carry airborne lidar often, fly at altitudes of 100-500 m where ships are easily spotted and avoided. Many lidar systems used in oceanographic experiments already meet current laser safety standards. Since the attenuation of light energy in water is high, the energy density of a laser beam decreases rapidly once it enters the water column. Therefore, we focused on potential effects from laser beam contact on cetaceans and pinnipeds at the surface where the potential for damage is greatest.

We are unaware of any studies conducted on laser injury to marine mammals. However, much research has been done to determine damage thresholds for humans. There are also a number of studies on cetacean and pinniped eyes. We make approximate quantitative estimates of damage thresholds for both cetacean and pinniped eyes and suggest areas for further research to improve these estimates. We conclude that airborne lidars operated under current laser safety standards will not cause damage to cetaceans or pinnipeds.

LASER SAFETY AND RETINAL DAMAGE

In 1973, the first national consensus on laser safety was issued by the American National Standards Institute (ANSI 1973) and has since been updated (ANSI 1993). ANSI developed energy and power safety limits, called maximum permissible exposures (MPEs), for both ocular and skin exposures. The MPEs are based upon the wavelength of the radiation and the exposure time and are given either in energy per unit area (Joules/cm^2) or power per unit area (Watts/cm^2). The MPEs were also called threshold limit values by the American Conference of Government Industrial Hygienists, and were described as follows (Sliney and Wolbarsht 1980):

> *"The threshold limit values are for exposure to laser radiation under conditions to which nearly all workers may be exposed without adverse effects. The values should be used as guides in the control of exposures and should not be regarded as fine lines between safe and dangerous levels. They are based on the best available information from experimental studies."*

Although the applications of lidars for oceanographic experiments vary greatly, the wavelengths and pulse widths used are fairly consistent. Most oceanographic lidars operate in the blue-green region of the visible spectrum (400-700 nm). At these wavelengths, water has a lower absorption coefficient and the laser beam exhibits greater depth penetration than UV (200-400 nm) or infrared (700-1400 nm) light. The 532-nm wavelength of the Nd: YAG laser is commonly used. A pulse width of about 10 ns is often used providing a depth resolution of about 1 m. Longer pulse widths degrade depth resolution and result in less discrimination of underwater targets. At this wavelength and pulse width, the laser energy has to be higher than $2x10^{-2}$ J/cm^2 to cause any skin damage to humans (ANSI 1993). Because of the focusing power of the eye, lesser amounts of energy may still cause retinal damage. We will, therefore, conservatively concentrate on injuries to the eye.

The ocular damage mechanism depends on two factors. First, the wavelength of the radiation affects absorption within different structures of the eye. For example, ultra-violet light is absorbed in the cornea and the lens, whereas visible light is transmitted through the cornea and lens to the retina. Since we are interested in wavelengths in the visible region, potential damage will be to the retina and choroid and not the cornea or lens. Second, the damage mechanism is highly dependent upon the pulse width of the laser beam. For pulses longer than 10^{-6} seconds, the primary damage mechanism is thermal. At pulse widths less than 10^{-6} seconds, the damage mechanism is a combination of thermal and photo-acoustical effects (Allen 1980). The contribution of each mechanism depends on the energy level and is not fully known. At threshold, the main mechanism is probably thermal. Hayes and Wolbarsht (1968) suggested that damage occurs primarily in the pigment granules of the retinal pigment epithelium (RPE). Light is transmitted through the neural layers of the retina to the RPE and choroid (Sliney 1984). For short pulses, the RPE increases in temperature by only about 5 degrees, while the pigment granules can increase over 1,000 degrees (Sliney and Wolbarsht 1980, Hayes and Wolbarsht 1968). With this rapid heating of the pigment granules, acoustic transients may cause damage to nearby structures (Allen 1980, Sliney and Wolbarsht 1980). At suprathreshold levels, photo-acoustical effects dominate, becoming highly destructive, almost "explosive" (Sliney 1984).

The MPE for human ocular injury is 5×10^{-7} J/cm^2 for laser energy with a wavelength between 400 nm and 700 nm and an exposure time of 10^{-9} to 1.8×10^{-5} seconds (ANSI 1993). Although there may be variations in the wavelength and pulse width between different lidar systems, the oceanographic systems we address in this study are limited to these parameters.

Because potential damage is to the retina, RPE, and choroid, it is useful to determine the likely energy density on the retina resulting from exposure to a laser beam. The energy density at the retina depends on the image size for a point source or a collimated beam. The energy per unit area on the retina is:

$$E_r = \frac{E_c A_c \tau}{A_r},$$

where E_r is energy density at the retina, E_c is energy density at the cornea, τ is transmission through the eye to the retina, A_r is area of the image, and A_c is area of the pupil. We will assume that τ is close to 1, because most of the visible light is transmitted through the cornea and lens to the rod and cone receptors in the retina. We will also assume A_r is equivalent for circular and noncircular pupils. If a pupil is circular then A_c and A_r are:

$$A_c = \frac{\pi}{4} d_e^2, A_r = \frac{\pi}{4} f_e^2 \rho^2,$$

where d_e is the pupil diameter, f_e is the focal length, and ρ is the visual acuity. Then, the energy density at the retina is:

$$E_r = \frac{E_c d_e^2}{f_e^2 \rho^2}.$$

Given any MPE, we can calculate the energy density limit at the retina for various laser parameters and operational conditions.

Eye Anatomy of Cetaceans and Pinnipeds

Before we can determine damage thresholds for cetaceans and pinnipeds, we need to examine the differences between the human eye and the cetacean and pinniped eyes. These

marine mammals have adapted to environmental problems, which are different from those of most terrestrial mammals. Since we are concerned with the visual acuity of these marine mammals, the optical adaptation to vision in air and water is important. In addition, the adaptation to vision in bright sunlight and almost total darkness will be significant.

In humans and most terrestrial mammals, the cornea is the primary refractive element. In water, the cornea is ineffective because the cornea's index of refraction is too close to the index of refraction of water. Most aquatic animals, including cetaceans and pinnipeds, have compensated for this by developing a spherical lens which acts as the primary refractive element (Walls 1963). The cornea has little curvature, and functions much like a diver's mask. However, animals that need to see well both in air and underwater must adapt to the effects of any remaining curvature of the cornea. Accommodation, a change of the curvature of the lens or the distance from the lens to the retina, is the most common mechanism (White and White 1996). In humans, accommodation is accomplished when ciliary muscles alter the curvature of the lens, thus changing its refractive power.

West *et al.* (1991) found three species of pinnipeds that have well-developed ciliary muscles. They suggested that the ciliary muscles might be used to move the lens toward the retina to correct for the myopia, or nearsightedness, produced by the cornea-water interface. However, research has shown that cetaceans do not have well-developed ciliary muscles (West *et al.* 1991). Therefore, cetaceans probably cannot use this technique to correct for the effects of the cornea when out of the water. Cetaceans, however, have well-developed extraocular muscles. Dawson (1980) suggested that these muscles may be used to change the diameter of the eye and thus compensate for the changed focal length, but no research has been done to prove this.

Bottlenose dolphins have elliptical pupils in moderate light, which constrict to two pinholes at high luminance levels (Herman *et al.* 1975). Herman *et al.* (1975) attributed the

almost equal acuity in air and underwater of bottlenose dolphins to the optical effects of the pinholes. In bright light, constriction creates a stenopaic pupil, or pinhole, which increases the depth of field and reduces the cornea to a flat surface with no refractive powers. This results in good visual acuity in air at high luminance levels. At lower luminance levels, the pupil becomes elliptical and the dolphin is myopic in air with low visual acuity. In water, the cornea has little refractive power, resulting in visual acuity independent of pupil size. However, Herman *et al.* (1975) had no data to support this correlation (Dawson 1980).

Schusterman (1972) came to a similar conclusion concerning pinnipeds after a behavioral study of one California sea lion. The visual acuity of the sea lion was measured for varying levels of luminance, both in water and in air. In air, visual acuity dropped rapidly with decreased background light. In water, visual acuity also declined as the luminance was decreased, but not as rapidly as in air. Instead of constricting to two pinholes, the pupil of some pinnipeds constricts to a vertical slit (Schusterman 1972). Schusterman concluded that the vertical slit acts as a pinhole in the horizontal axis. He believed pinnipeds to have an oval-shaped cornea in the vertical axis, resulting in an unevenly focused image, or astigmatism. The combination of the refractive power of the cornea and the astigmatism results in an effectively emmetropic, or normal, eye.

However, there is much debate over both of these conclusions (White and White 1996). A behavioral study in 1979 concluded that constriction of the pupil to two pinholes might not be the main mechanism for environmental adaptation (Dawson *et al.* 1979). Dawson *et al.* (1979) measured the pupil area for different luminance levels and found the pupil to be 70 mm^2 fully dilated and about 5 mm^2 fully constricted. They then conducted two behavioral studies and found the dolphin's response to visual tasks had no dependence on the luminance level (or pupil size) until there was not enough light to see. They also found evidence to suggest that the dolphin's pupil was not fully constricted in the visual acuity study conducted by Herman *et al.* (1975).

In addition, a recent study found no evidence of astigmatism in the hooded seal (Sivak *et al.* 1989) and concluded that the hooded seal eye is slightly hyperopic (far-sighted) in water and slightly myopic (near-sighted) in air. The vertical slit, hypothesized to account for good visual acuity in air, was never seen and they concluded that the vertical slit is only present in extremely bright light (Sivak *et al.* 1989).

Since both pupil size and visual acuity are used to calculate the retinal image size, the dependence of visual acuity on pupil size must be known to make an accurate estimate of exposure limits for cetaceans and pinnipeds. It is apparent that cetaceans and pinnipeds have good visual acuity at high luminance levels both in water and in air (Herman *et al.* 1975). However, at high luminance levels, the pupil size is reduced. At lower luminance levels, the pupil is larger, but the acuity is reduced. There is evidence to suggest that the acuity of pinnipeds declines with decreased luminance more quickly in air than in water (Schusterman 1972). Behavioral research directly correlating pupil size to visual acuity in air is necessary before precise estimates of laser exposure limits can be made. However, we can make a conservative estimate if we assume a combination of the best acuity and the largest pupil, a combination that will not be found in nature.

Cetaceans and pinnipeds have adapted to living in bright sunlight and dark ocean waters. In bright light, a highly constricted pupil keeps the energy levels down, while in darker conditions, a pupil can be fully opened to admit as much light as possible. Both have developed the tapetum lucidum to function as a light gathering device within the eye. The tapetum lies behind the RPE within the choroid and acts as a reflective layer, effectively increasing the total amount of available light to the rod and cone receptors in the retina (Dral 1977). There are two types of tapeta. Cetaceans have a tapetum fibrosum (Young *et al.* 1988), which is formed with extracellular collagen fibrils. Pinnipeds have a tapetum cellulosum (Jamieson and Fisher 1972), that is formed with intracellular reflective rodlets. In most terrestrial mammals the fundus is

only partially tapetalized, covering just the lower vision field. However, the tapetum in cetaceans and pinnipeds completely covers the fundus (Dral 1977, Dawson, *et al.* 1972, Dawson *et al.* 1987). With the horizonless environment cetaceans live in, there is not the large distinction between upper and lower field of vision that there is with terrestrial animals. Therefore, the development of a fully tapetalized fundus appears to reflect the homogeneity of the ocean environment (Young *et al.* 1988).

Young *et al.* (1988) counted the average number of tapetal layers for *Tursiops spp.* and *Kogia spp.* to be 51 and 74, respectively, and reported that cetaceans have a large number of tapetal layers compared with other mammalian species. Jamieson and Fisher (1972) measured 20-22 layers in the harbor seal and 32-34 layers in the harp seal. The tapetum of the grey seal has been measured at 30-35 layers (Braekevelt 1986). In comparison, cats have a tapetum cellulosum with 15-20 layers (Braekevelt 1990), and tapetums for other mammalian species have been measured between 6 and 20 layers (Young *et al.* 1988).

The actual reflectivity of the tapetum fibrosum in cetaceans and tapetum cellulosum in pinnipeds has not been measured. Theoretically, the more tapetal layers the structure has, the closer to 100% reflective it becomes. Young *et al.* (1988) hypothesized that the tapeta of the *Tursiops spp.* and *Kogia spp.* should, therefore, be a highly efficient reflector. At the very least, the reflected light per unit area of the bottlenose dolphin should be higher than that of a cat's tapetum (Dawson 1980). Since pinnipeds have more cell layers than cats and the pinniped tapetum is fully tapetalized, we can assume that the tapetum in pinnipeds reflects more light than a cat's tapeta. Using a measured reflectivity of 44% for cats (Lee *et al.* 1992, Weale 1953), we assume that at least 44% of the laser light will be reflected back toward the retina for cetaceans and pinnipeds. Consequently, less than 66% of the light will be transmitted to the choroid. To obtain better estimates of the amount of light transmitted and reflected, further research needs to be conducted on the reflectivity of the tapetum lucidum in both cetaceans and pinnipeds.

With the presence of the tapetum lucidum, the number of pigment granules in the RPE decreases. Murayama *et al.* (1992) found the tapetum thickest in the fundus area and thinnest in the peripheral area. Correspondingly, pigment granules were most abundant in the peripheral areas. Other researchers have found similar results for both cetaceans and pinnipeds (Dral 1977, Jamieson and Fisher 1972).

With the existence of the tapetum lucidum and the lack of pigment granules, the mechanism for retinal damage for cetaceans and pinnipeds will probably be different from that of humans. At suprathreshold levels, damage will occur regardless of the presence of the tapetum or the number of pigment granules. At threshold levels, the main mechanism for radiation damage to the human eye involves thermal absorption by pigment granules in the RPE. With fewer pigment granules in the RPE of cetaceans and pinnipeds, most of the energy will be transmitted through the RPE to the choroid. The tapetum will reflect a portion of the light back toward the retina. The remaining energy will either be absorbed in the tapetum or transmitted to the rest of the choroid. According to Hayes and Wolbarsht (1968), thermal absorption by choroidal pigment granules can result in damage to nearby blood vessels. Therefore, it is possible that the primary damage in cetaceans and pinnipeds would occur in the choroid, with secondary damage to the surrounding structures. However, the risk of damage is dependent on the reflectivity of the tapetum, with higher reflectivity's reducing the risk. Cetaceans and pinnipeds may have a higher damage threshold than humans because of the existence of the tapetum lucidum. However, to obtain a conservative estimate of the exposure limit, we assume that the energy threshold at the retina and choroid is the same for all species, regardless of the damage mechanisms at work.

Visual Acuity

A number of studies have been conducted on the visual acuity of cetaceans and pinnipeds

(Table 1). Visual acuity measurements were obtained from either behavioral or ganglion cell-distribution studies.

Behavioral studies conducted in the 1970s correlate reasonably well with each other (Schusterman 1972, Pepper and Simmons 1973, Herman *et al.* 1975). In each study, marine mammals were taught to perform a certain task (i.e. press a lever) to signal discrimination between two gratings. Using the number of correct responses by the mammals, the distance to the gratings, and the spacing of the gratings, a range of visual acuity was determined for various species.

More recently, a number of researchers have studied retinal resolution (Dral 1977, 1983; Mass 1986, 1992, 1993, 1996; Mass and Supin 1990, 1992; Murayama *et al.* 1992). By measuring the ganglion cell distribution, the retinal resolution can be determined (Mass 1992).

$$D = d\left(\frac{N\pi}{180°}\right)^2,$$

Ganglion cell distributions are measured in cells/mm^2 and then converted to cells/deg^2 using: where D = density in cells/deg^2, d = density in cells/mm^2, and N = posterior nodal distance in mm. Posterior nodal distance is equal to focal length. The distance between ganglion cells is

$$s = D^{-1/2},$$

equivalent to the retinal resolution (Collin and Pettigrew 1989) and is equal to:
where s = the spacing between cells (Mass 1992). If we assume that an animal's optics will never produce a better resolution than the retina can detect, then retinal resolution should be approximately equivalent to the best possible visual acuity (Mass and Supin 1997).

To calculate the sensitivity ratio, the pupil diameter or area, the focal length, and the resolution must be known for the human eye and the specific species in question. Values of d_e = 7 mm, f_e = 17 mm, and ρ = 1' were used for the human eye (Sliney and Wolbarsht 1980). The current data for cetaceans and pinnipeds are summarized in Table 1. Focal lengths for the marine mammals were taken directly from the literature or inferred from drawings. The pupil diameters and areas were a little more difficult to determine. Most articles did not give approximate pupil sizes. When available, lens diameters were used to approximate pupil diameters because we assumed that the pupil diameter would never be larger than the lens diameter. Given the available data, we calculated a range of sensitivity ratios.

The last column in Table 1 lists the sensitivity ratio for each species. The sensitivity ratio is:

$$\gamma = \frac{E_{rs}}{E_{rh}},$$

where E_{rs} is the energy density on the retina of the specific species and E_{rh} is the energy density on the retina of a human. We can now make an estimate on the maximum exposure limits for cetaceans and pinnipeds; the limit for a particular species is the human limit divided by the sensitivity ratio for that species; in all cases, this limit is greater than the human limit.

Up to this point, we have considered the potential effects of a single pulse with the energy equivalent of the human eye-safe standard (5×10^{-7} J cm^{-2}). The implicit assumption has been that the airborne laser is moving so quickly that an animal would only be exposed to a single pulse as the aircraft passes overhead. However, this may not always be the case. The number of consecutive pulses that expose any particular point on the surface satisfies the following inequality:

$$N\ LE\ \frac{D\ F}{V} + 1,$$

where D is the spot diameter on the surface, F is the pulse repetition frequency, and V is the speed of the aircraft. Thus for $DF < V$, spots on the surface do not overlap, and N is 1. For $V < DF < 2V$, animals in certain positions relative to the spots could be exposed to 2 pulses. This condition is shown schematically in Figure 1. Animals within both circles would receive 2 exposures, and animals with one circle would receive 1 exposure.

To prevent laser damage from multiple exposures one should reduce the energy in each pulse by some factor. Although the effects of a few pulses are not well understood, for an exposure to N pulses, it is certainly safe if the energy in each pulse is reduced by a factor of N^{-1}. When this factor falls below the long-exposure limits discussed next, the appropriate one of those limits may be used instead.

For a repetitively pulsed laser with pulse length less that 18 s, the energy in each pulse must be reduced for multiple exposures greater that 1 Hz. No reduction is necessary if F is less than 1 Hz. For 1 Hz $< F <$ 300 Hz, the energy in each pulse must be reduced to $5 \times 10^{-7} F^{-1/2}$. For multiple exposures between 300 and 34,000 Hz, the laser energy in each pulse should be reduced to 3×10^{-8} J cm^{-1}. For multiple exposures exceeding 34,000 Hz, the total energy becomes important as the damage mechanism is probably mostly thermal. For these more rapid multiple exposures, the laser energy in each pulse should be reduced to $1.8 \times 10^{-3} t^{-1/4} F^{-1}$.

Our analysis indicates that pinnipeds and cetaceans have less resolving capability than humans, and therefore, human eye-safe standards may be excessive for pinnipeds and cetaceans. The eye-safe standards for single and multiple-pulse exposures to the marine mammals we have

examined could be increased by a factor equal to the maximum sensitivity ratio for each species (Table 1).

A worst case might be one in which a helicopter is hovering over an animal that is staring into the beam. This analysis is valid as long as the exposure is less than 10 seconds. While the likelihood of this case can be debated, evaluation of the risk is straightforward using the human sensitivity ratio (1.0) or the species-specific sensitivity ratio. For multiple exposures between 300-34,000 Hz, the energy density for each pulse should be less than 3×10^{-8} J cm^{-2} instead of the human, single-pulse exposure limit of 5×10^{-7} J cm^{-2}. This pulse energy would be eye safe for all species. However, if we ensure that no people were going to be illuminated, we could probably increase the exposure in relation to the sensitivity ratio of the most sensitive species we expect to encounter. As an example, the fur seal, *Callorhinus ursinus*, has a calculated sensitivity ratio of 0.167. The single-exposure limit would be 3×10^{-6} J cm^{-2}, and the 10-s limit for 300-34,000 Hz would be 1.8×10^{-7} J cm^{-1} per pulse.

Discussion

We conclude from our investigation that oceanographic lidars that meet current human laser safety standards will have no harmful effects on the eyes of cetaceans or pinnipeds, because the human eye is more sensitive to laser radiation than either the cetacean eye or the pinniped eye. If there is no chance of the laser beam coming in contact with humans, then the laser power can be increased to an exposure limit applicable to the most sensitive of the marine mammals in the region of the experiment. For example, it appears that pinnipeds are more sensitive than cetaceans. Therefore, if an experiment is conducted in deep, offshore ocean waters, the applicable exposure limit could be higher than a similar experiment conducted over coastal waters where pinnipeds are more likely to be encountered.

We are confident in our conclusions because we believe the sensitivity ratio estimates are conservative. We believe that the existence of the tapetum lucidum increases the energy threshold for retinal injury in cetaceans and pinnipeds. In addition, the largest possible pupil diameter was used in calculating the energy density on the retina. It is unlikely an animal would have fully dilated pupils at the surface. Some studies have shown that visual acuity in the California sea lion drops significantly with decreasing background luminance. It may be that the best visual acuity in air should only be used with a small pupil diameter and that the larger pupil size should be used with a low acuity.

Although the likelihood that an oceanographic lidar's laser beam would directly contact a cetacean or pinniped eye is unknown, both cetaceans and pinnipeds spend a significant amount of time underwater and are widely scattered at sea. Large groupings at sea are generally easy to spot and could be either avoided or the laser beam momentarily disengaged. We believe the probability of an animal staring directly into a laser beam is small, but have provided an analysis that addresses the inadvertent exposure of cetaceans and pinnipeds to laser energy.

ACKNOWLEDGMENTS

We would like to thank Dr. D. Sliney for his helpful suggestions concerning laser safety. We would also like to thank Dr. W. W. Dawson for sharing his wealth of knowledge on cetaceans.

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Table 1 Summary of available data and estimated sensitivity ratios for several species.

Animal	Body Length (m)	Focal Length (mm)	Lens Diameter (mm)	Pupil Diameter (mm)(max)	Res. (Behavioral) (min of arc)	Res. (Retinal) (min of arc)	Sensitivity Ratio
Cetaceans							
Eschrichtius gibbosus (Gray Whale)	13 [2]	23 [11,15]	*11.8 [15]			11'-14' [11,15]	0.008-0.013
Balaenoptera acutorostrata (Minke Whale)	9 [2]	**40 [16]				7.1', 7.6' [16]	~0.027-0.031
Tursiops truncatus (Bottlenose Dolphin)	2.4 [3]	16 [4] 14.5 [10,14]		10 [3]	12'-19' -air [6] 8'-14' -water [6] 18' -air [17]	10' [4] 12' -air [10,14] 9' -water [10,14]	0.006-0.043
Delphinus delphis (Common Dolphin)	2.1 [2]	16 [5]	***10			8'-9.5' [5]	0.026-0.036
Phocoena phocoena (Harbor Porpoise)	1.8 [2]	11.5 [13]	9 [8]	8 [8]		11'-14 [10]	0.014-0.03
Phocoenoides dalli (Dall's Porpoise)	1.8 [2]	**12.5 [16]	***9			11.6', 12.2' [16]	0.02-0.023
Pinnipeds							
Odobenus rosmarus (Walrus)	3.7 [2]	12.5 [9]	11.5 [19]			7.8' [9]	0.083
Eumetopias jubatus (Steller's Sea Lion)	3 [2]				6.5'-7.5' -water [18]		0.053-0.071
Callorhinus ursinus (Fur Seal)	2.1 [2]	22.5 [13]	*15.9 [13]			4.2'-5.4' [13]	0.01-0.167
Zalophus californianus (California Sea Lion)	2 [2]		14.4 [19]		5'-9' -water [19]		~~~0.038-0.125
Phoca vitulina (Harbor Seal)	1.8 [1]	*22 [7]	*16.7 [7]		8.1'-8.6' -water [18]		0.045-0.053

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* Measured from diagram from reference
** Calculated from formula (see Mass 1992)
*** Estimated from lens or pupil diameter for similar species
~Calculated using the focal length to lens diameter ratio found for the gray whale.
~~Calculated using the focal length to lens diameter ratio found for the fur seal.
~~~Calculated using the average of the focal length to lens diameter ratios found for the fur seal and the harbor seal
~~~

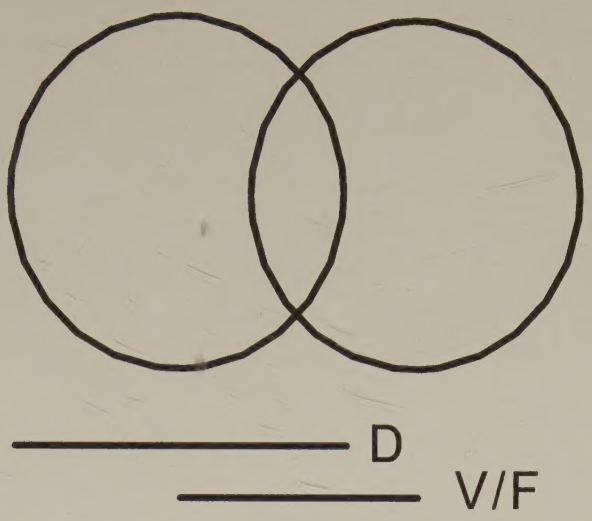

Figure 1 Geometry of overlapping spots of diameter *D* on surface for aircraft speed *V* and pulse-repetition frequency *F*. Overlap area is area where 2 exposures are possible.